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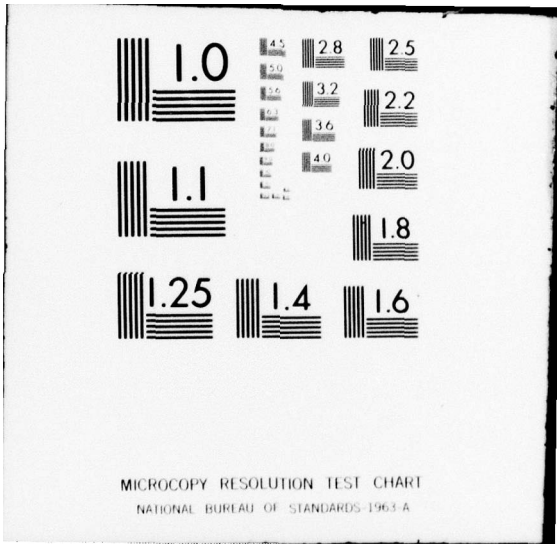
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MECHANICAL BEHAVIOR OF TITANIUM ALLOYS

TECHNICAL REPORT

Submitted to:

Office of Naval Research

By:

L. A. Ahlberg, O. Buck, and N. E. Paton

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MECHANICAL BEHAVIOR OF TITANIUM ALLOYS
(Effects of Hydrogen on Anisotropic Elastic Properties of bcc Ti Alloys)

February 1977 to February 1978

Submitted to:
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The effects of hydrogen in solid solution on the anisotropic second order elastic constants of Ti-40V and their temperature coefficients have been determined. Using recently published pressure derivatives of hydrogen-free materials we were able to separate out intrinsic alloying effects (due to hydrogen doping) from those due to the accompanying lattice parameter change. The intrinsic effects, which are electronic in nature, are found to be positive and those due to the lattice parameter change are negative. Furthermore,

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it is shown that the anisotropy factor increases with increasing hydrogen concentration. Some implications of these observations are briefly discussed.

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EFFECTS OF HYDROGEN ON ANISOTROPIC ELASTIC PROPERTIES OF bcc Ti-ALLOYS

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The relatively large effects of hydrogen on yield strength, Young's modulus (and its temperature dependence) and the lattice parameter of metastable (bcc) Ti-alloys have been known for some time (1-4). In this class of materials, the room temperature solubility of H is quite large, so that hydride formation does not interfere with the measurements. Some of the work (2) showed that both yield strength and Young's modulus decrease with increasing H content, while the lattice parameter increases. These results have been interpreted in terms of a predominantly electronic interaction between H and the host lattice. It is now know (5) from the H dependence of second order elastic constants and the lattice parameter, as well as third order elastic constants, that the observed changes in second order constants can be separated into those due to volume changes and those from intrinsic alloying modifications of the interatomic forces, the latter being basically electronic in nature. Since third order elastic constants for the Ti-V system have been determined recently (6), it seemed worthwhile to measure the hydrogen sensitivity of the (anisotropic) second order elastic constants (a combination of which determines the Young's modulus). Such information would allow us to obtain insight into the physical effects of H on the alloy system and its effect on the plastic deformation of bcc metals (7). The present note reports on some of our observations on the Ti-V-H system.

As described earlier (8), an ultrasonic phase comparison technique was used to determine both the values of the pure-mode ultrasonic sound velocities (at about 12 MHz) and their dependence on H and temperature. From these data, the second order elastic constants C_{ij} can be determined (9). The specimen used for these measurements was a single crystal of Ti-40V alloy which was cut to expose a parallel pair of {100} faces (0.516 cm apart) and a parallel pair of {110} faces (0.848 cm apart). This specimen was charged in a micro-Sieverts apparatus with various amounts of H at 800°C.

Table I summarizes the second order elastic constants C_{11} and C_{44}, as well as important combinations of C_{ij} such as $C' = (C_{11} - C_{12})/2$ (a shear constant) and $B = (C_{11} + 2\,C_{12})/3$ (the bulk modulus), as a function of four hydrogen levels. Furthermore, the anisotropy factor $A = C_{44}/C'$, which is a measure of the lattice instability, is given in Table I. This quantity A is of some interest to the present studies since the metastable Ti-V alloys undergo a lattice transformation [the athermal $\beta \rightleftharpoons \omega$ transformation (10)] at low temperatures, which seems to be affected by the presence of H (3). As was pointed out by Zener (11), bcc lattices with a large A tend to be unstable and effects of H on A should give an indication of the transformation behavior of the alloy. As seen from Table I, C' is the elastic property that is most severely affected by H (in the average about -2.6% per a/o H). Therefore, A is rapidly increasing with H, indicating that the lattice becomes more unstable. We also noticed that the attenuation of the acoustic signal, that is used to determine C , increases sharply with increasing H concentration. This attenuation is caused by the $\beta \rightleftharpoons \omega$ transformation, as discussed earlier (1-4). Thus, the large changes in A, C' , and the attenuation suggest

strongly that the $\beta \rightleftharpoons \omega$ transformation temperature is raised with increasing H concentration.

Table II summarizes the temperature dependence of the quantities given in Table I. Particularly noticeable is the change in sign for dC_{11}/dT and dC'/dT (and therefore dA/dT) with increasing H concentration. It is now clear that the change in temperature behavior of the Young's modulus with increasing H, as observed on both Ti-V (3) and Ti-Mo (2.4) alloys at room temperature, is mainly due to either the contribution from dC_{11}/dT or dC'/dT or both.

Based on the present second order elastic constants data and their changes with H concentration, we can now separate the extent to which the observed changes are caused by the intrinsic alloying effect (isovolumetric changes) from those due to the lattice parameter change, which accompanies the addition of hydrogen. This was recently demonstrated for the NbH system (5), where it was postulated that any elastic modulus M is a function of H concentration, c, and the average lattice spacing, a, so that the total change with c can be written as

$$\frac{dM}{dc} = \left.\frac{\partial M}{\partial c}\right|_a + \left.\frac{\partial M}{\partial a}\right|_c \frac{da}{dc} \qquad (1)$$

Rewriting Equation (1) yields the relative intrinsic alloying effect

$$\frac{1}{M}\left.\frac{\partial M}{\partial c}\right|_a = \frac{1}{M}\frac{dM}{dc} - \frac{1}{M}\left.\frac{\partial M}{\partial a}\right|_c \frac{da}{dc} \qquad (2)$$

with

$$\frac{1}{M}\left.\frac{\partial M}{\partial a}\right|_c \frac{da}{dc} = -\frac{B}{M}\frac{dM}{dp}\frac{3}{a}\frac{da}{dc} \qquad (3)$$

where dM/dp is the pressure derivative of a modulus M and a the lattice parameter. dM/dp have been measured recently (6) for 0 a/o H and are given in Table III. da/adc was determined in the present investigation to be da/adc = 6.9×10^{-4} per a/o H. We thus are able to estimate the intrinsic alloying effect for M = C_{11}, C_{44}, B, and C' with the results given in Table IV. As one might expect, these intrinsic effects (electronic in nature) of H on the moduli M turn out to be positive and those due to the lattice parameter change are all negative.

These results open up further avenues of research. For instance, the authors believe that an accurate knowledge of the anisotropic elastic moduli will be useful to determine the H dependent shear stress τ, necessary to move a dislocation on the appropriate slip plane (12). On the other hand, the data may give us a better understanding on the effects of H on the $\beta \rightleftharpoons \omega$ transformation. Our results show that the anisotropy factor A increases with increasing H concentration. As indicated in Fig.1, plotting A as a function of V concentration and as a function of H in Ti-40V yields (at low H concentrations) basically the same slope for both curves if the addition of 1 a/o H is equivalent to the extraction of 1 a/o V. Such an equivalence was speculated about earlier (3) without quantitative proof. The meaning of this observation would be that the hydrogen attracts basically one electron from the vanadium. Furthermore, we should note that the effects of H on C' are so large [in particular in respect to NbH (5)] that there is good reason to believe that the H (actually H^-, if the previous statement is valid) gives rise to a large tetragonal distortion of the Ti-V lattice (13).

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TABLE I

Anisotropic second order elastic constants of Ti-40V, doped with H, at 22.5°C. All values, except A (dimensionless), in 10^{11} dyn/cm^2.

	0 a/oH	2.4 a/oH	3.6 a/oH	4.8 a/oH
C_{11}	14.88	14.77	14.65	14.45
C_{44}	4.053	4.076	4.085	4.104
C	2.399	2.293	2.223	2.114
B	11.880	11.710	11.690	11.630
A	1.690	1.780	1.840	1.940

TABLE II

Temperature derivatives of the second order elastic constants of Ti-40V doped with H, at 22.5°C. Units of first four derivatives in 10^7 dyn/cm^2 °C. dA/dT: in 10^{-4}/°C.

	0 a/oH	2.4 a/oH	3.6 a/oH	4.8 a/oH
dC_{11}/dT	-17.84	-10.43	-4.37	+9.33
$dC/_{44}/dT$	-4.18	-4.04	-3.77	-2.88
dC' /dT	-6.71	-1.60	+0.44	+7.88
dB/dT	-8.89	-8.30	-4.96	-1.18
dA/dT	+2.99	-0.52	-2.06	-8.60

TABLE III

Pressure derivatives of second order elastic constants of Ti-38.5V, from Reference 6 (all units dimensionless).

dC_{11}/dP	dC_{44}/dP	dC'/dP	dB/dP
4.63	0.431	0.533	3.92

TABLE IV

The effects of H on the moduli on Ti-40V (all units in 10^{-3} per a/oH)

1st column: measured values.
2nd Column: changes due to lattice expansion.
3rd column: Changes due to intrinsic effects.

M	$\frac{1}{M}\frac{dM}{dc}$	$\frac{1}{M}\frac{\partial M}{\partial a}\Big\|_c \frac{da}{dc}$	$\frac{1}{M}\frac{\partial M}{\partial c}\Big\|_a$
C_{11}	-6.02	-7.65	+1.63
C_{44}	+2.42	-0.26	+2.68
C'	-2.47	-5.46	+2.99
B	-2.73	-8.11	+5.98

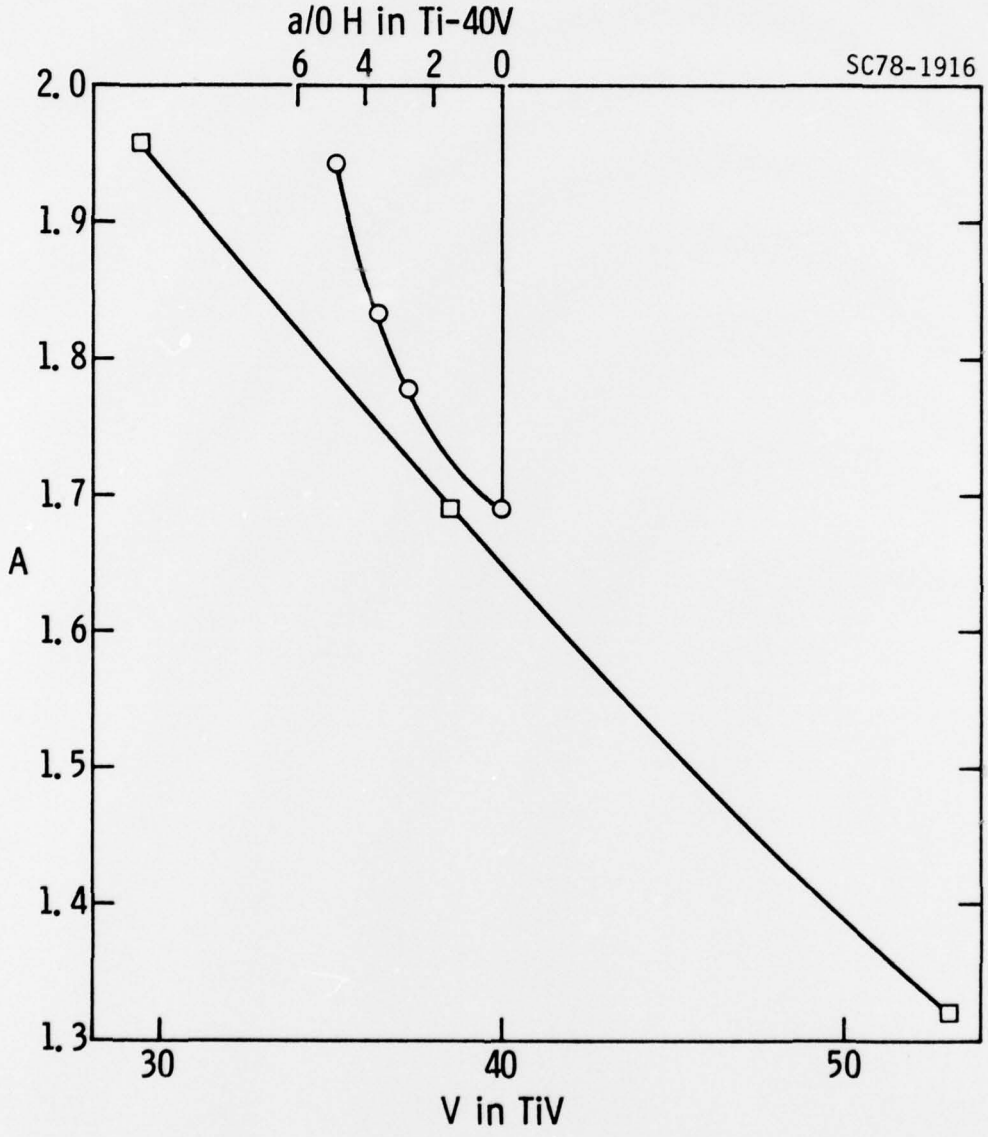

Fig. 1. The change of anisotropy factor with vanadium in Ti-V (6) and hydrogen concentration in Ti-40V.